NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

63-3-6 Enclosure (1)
C1-25-1643

406168

REPORT NO. LB-31253

SIMULATOR STUDY OF DIRECT LIFT CONTROL

DURING CARRIER LANDING APPROACHES

406 168

April 8, 1963

DOUGLAS AIRCRAFT DIVISION • LONG BEACH, CALIFORNIA

DOUGLAS

REPORT NO. LB-31253

SIMULATOR STUDY OF DIRECT LIFT CONTROL DURING CARRIER LANDING APPROACHES

April 8, 1963

Contract No. NOw 61-0404-t

Task Order No. 61-8

DOUGLAS AIRCRAFT COMPANY, INC.

LONG BEACH, CALIFORNIA

FOREWORD

This report is the final report of a fixed-base simulator study of direct lift control in carrier landing approaches as a means of improving glide path control precision. The study was initiated in 1960 as a part of the Douglas Aircraft Company research program and continued in 1961 under U. S. Navy Bureau of Weapons Contract NOw 61-0404-t, Task Order No. 61-8. The cognizant BuWeps engineers were Mr. William Koven and Mr. Harold Andrews, Stability and Control Unit, Airframe Design Branch, Aircraft Division. El Segundo Bureau of Naval Weapons Representatives were particularly cooperative and valuable as a source of experienced carrier pilot subjects. Their contributions were of immeasurable value to the program.

1.0 SUMMARY

The Combat Aircraft Division of the Douglas Aircraft Company, under contract to the Bureau of Naval Weapons, conducted fixed-base simulator tests of direct lift control during carrier landing approaches as a means of increasing flight path control precision.

The direct lift control system that was tested consists of controlling the trailing-edge flaps of a Model A-3 ± 10 degrees from the normal 35-degree deflection at normal flight control rates. Control of the flaps was achieved through a three-position switch on the control stick, operating in the same sense as the basic longitudinal control and trim. The system was designed to supplement and not replace normal longitudinal control.

During the course of the subject investigation, the effectiveness of direct lift control was evaluated over a wide range of aerodynamics characteristics variations, including phugoid and short-period mode frequency and damping, and operation on the backside of the power-required curve.

Direct lift control provided nominal improvements in landing approach, flight path control precision in those cases with good handling qualities or stability and control characteristics and considerable improvements in those cases with substandard handling qualities. Pilot opinion was strongly favorable to direct lift control although the quantitative effects were in some cases only nominal. Although the effects of direct lift control on minimum usable approach speed were not evaluated directly, improvements in flight path control precision and apparent handling qualities can reasonably be expected to permit reductions in minimum usable approach speed.

Installation and flight tests of direct lift control in appropriate carrier-type aircraft are recommended. The flight test program should include the following considerations:

1. Direct lift control system authority.
2. Minimum usable approach speed effects.
3. Feasibility and effectiveness of an integrating trim function in the direct lift control system.
4. Direct lift control system effectiveness in combination with an automatic throttle compensation system.
5. Operational procedures.

2.0 TABLE OF CONTENTS

2.1 List of Figures

2.2 List of Tables

2.3 List of Symbols

A_z	Acceleration normal to flight path - ft./sec.^{2}
A.N.D.	Airplane nose down
A.N.U.	Airplane nose up
C_D	Drag coefficient $\frac{\text{Drag}}{qS}$
$(C_D)_{C_L}$	Drag coefficient as a function of lift coefficient
ΔC_{D_c}	Increment of drag coefficient due to direct lift control
ΔC_{D_α}	Increment of drag coefficient due to angle of attack
C_L	Lift coefficient $\frac{\text{Lift}}{qS}$
$(C_L)_\alpha$	Lift coefficient as a function of angle of attack
ΔC_{L_c}	Increment of lift coefficient due to direct lift control
C_{L_T}	Rate of change of lift coefficient due to rate of deflection of trim surface - 1/sec.
D	Airplane drag - lb.
g	Acceleration of gravity - ft./sec.^{2}
h	Vertical distance of airplane above plane of carrier deck - ft.
i_g	Reference glide angle - radians
K	Coefficient or constant (with subscript a, b, c, 1, 2, or 3)
K	Speed dependent coefficient or constant (with subscript 4 or 5)
L.W.D.	Left wing down
m	Mass of airplane - slugs
P	Period - sec.
q	Dynamic pressure - lb./ft^2
R	Range - horizontal distance of airplane to reference contact point - ft.
R/C	Rate of climb - ft./sec.

RPM/RPM_{MAX}	Ratio of engine speed to maximum engine speed
R.W.D.	Right wing down
s	La Place operator - 1/sec.
S	Wing area - ft^2
T	Time constant (with subscript a or f) - sec.
T	Speed dependent time constant (with subscript b, c, d, 1, 2, or 3) - sec.
V	Velocity of airplane - ft/sec.
V_c	Velocity of carrier - ft/sec.
V_{RC}	Velocity with respect to carrier
W_P	Distance on oscilloscope between mirror reference lights - inches
X	Distance on airplane from reference contact point - ft.
X_{RMS}	Root-mean-square altitude error
Y	Lateral distance from airplane to reference glide path - ft.
Y_L	Lateral distance on oscilloscope of center of meatball from center of scope - inches
ΔZ_a	Vertical distance between airplane and reference glide path - ft.
Z_h	Vertical distance on oscilloscope of horizon above center of scope - inches
Z_L	Vertical distance on oscilloscope of mirror reference lights above center of scope - inches
Z_{MB}	Vertical distance on oscilloscope of meatball above mirror reference light on scope - inches
α	Angle of attack of fuselage reference line - deg.
$\Delta\alpha_s$	Change in angle of attack due to control stick deflection - deg.
$\Delta\alpha_T$	Change in angle of attack due to trim surface deflection - deg.
γ	Flight path angle - deg.
δ_a	Aileron deflection - deg.

δ_e	Elevator deflection - deg.
δ_F	Flap deflection - deg.
δ_s	Control stick deflection - deg.
$(\delta_s)_a$	Control stick deflection with respect to aileron deflection - deg.
$(\delta_s)_e$	Control stick deflection with respect to elevator deflection - deg.
δ_T	Throttle deflection - deg.
ζ	Damping ratio
θ	Line of sight pitch angle - deg.
ϕ	Angle of bank - deg.
$\Delta\dot{\phi}_s$	Rate of change of bank angle due to control stick deflection - deg.
ψ	Angle of yaw - radians
$\overline{30} - \overline{36}$	Analog computer potentiometer numbers

<u>Subscripts</u>

a	Airplane
e	With respect to the earth
L	Long-period characteristics
R	Random disturbance
S	Short-period characteristics
o	Initial condition

Note: Dot over term represents the derivative with respect to time, $\frac{d}{dt}$.

3.0 INTRODUCTION

Carrier landing approaches have always represented the ultimate in precise flight control. The precision required during carrier landing approaches has increased with the landing approach speed to the extent that altitude at the ramp must be controlled to within 6 feet of the ideal glide path in current high-performance carrier-based aircraft.

Development of the Mirror Landing System (MLS) has provided the precise altitude and glide slope reference required, but unfortunately the means of controlling altitude and glide slope in current high-performance aircraft leaves much to be desired. Altitude and rate of descent or climb are controlled by engine thrust on a long-term or steady-state basis and by longitudinal control on a short-term or transient basis. In an ideal carrier approach, the throttle would be set for the proper rate of sink at the desired trimmed approach speed, and the minor altitude corrections made with the longitudinal control. Larger altitude errors would be corrected through longitudinal and thrust control. Continuous control demands in one direction or another would be corrected via trim or thrust adjustment as necessary.

The relatively slow response of jet engines, the large thrust changes required to initiate rapid changes in the rate of descent or altitude, and the possibly adverse pitching moments due to power effects detract from the effectiveness of altitude control through power alone. The relatively high induced drag of highly swept, low-aspect-ratio wings of current high-performance aircraft at approach speeds and the introduction of longitudinal dynamics with characteristic lags and possible poor damping detract from altitude control effectiveness by longitudinal control.

The desire for increased flight path control precision and consideration of the deficiencies of available controls lead to consideration of direct lift control. Preliminary feasibility studies and a simple simulator test of direct lift control were conducted by the El Segundo Division of the Douglas Aircraft Company in 1960. The simulation was relatively crude, and the authority of the direct lift control somewhat large, but the results clearly indicated that direct lift control through trailing-edge-flap control was feasible and effective.

On the basis of these results and the expressed interest and encouragement from the Bureau of Naval Weapons, the simulation was refined in preparation for a more complete study of direct lift control with a more realistic authority. The current study was sponsored by the Bureau of Naval Weapons and conducted under BuWeps Contract NOw 61-0404-t, Task Order No. 61-8.

4.0 DISCUSSION

4.1 Description of Equipment and Tests

4.1.1 Simulator

A fixed-base simulator was used for the subject investigation. Photographs of the simulator and instrument panel are shown in Figures 1 and 2. A sketch of the instrument panel and simulated Mirror Landing System (MLS) is shown in Figure 3. The aerodynamic simulation included complete nonlinear simulation of the three longitudinal degrees of freedom and a simplified simulation of the two lateral degrees of freedom (roll and yaw). The lateral degrees of freedom were included to provide an additional task and make the simulation somewhat more realistic. No lateral maneuvering was permitted other than maintaining heading and keeping the wings level. Block diagrams of the control system, equations of motion, and simulated mirror landing system display are shown in Figures 4, 5, and 6, respectively. The equations used in the simulation are summarized in Table I. Vertical displacement of the "meatball" is primarily an indication of angular error from the desired glide path. As a consequence, its sensitivity to linear altitude errors is increased with reduced range. This phenomenon was included in the simulation.

The basic configuration, represented by test condition 2, was representative of a Model A-3B aircraft. The basic aerodynamic characteristics are summarized in Table II. Note that although lift and drag curve slopes are quoted in Table II, nonlinear lift and drag characteristics were used in the simulation. The quoted slopes are the gradients at the trimmed approach condition. Although Model A-3 aircraft have a control wheel, a Model A-4 control stick was used in the simulator. See Figures 1 and 2. The stick deflection range was 25 degrees aft, 15 degrees forward, and ± 36 degrees laterally. Linear springs with force gradients of 1.2 pounds per degree longitudinal stick deflection and 0.55 pounds per degree lateral stick deflection were used for control feel. A throttle or power level was provided for thrust or power control. No directional control was provided. The direct lift control system was actuated through an additional thumb switch on the stick grip.

4.1.2 Direct Lift Control System

The direct lift control system consisted of control of the flaps at high rates over a small range (± 10 degrees) about the nominal flap position (35 degrees). A flap deflection rate consistent with conventional control-surface rates, 40 degrees per second, was used over the 10-degree, direct lift control range. The 10-degree range was selected on the basis that this would be all that might be afforded on the Model A-3 because of aircraft performance and stall proximity considerations. In general, the authority of such a system would depend on the flap effectiveness, the desired approach speed, stall margin, and approach attitude. The authority of the tested system provided lift coefficient control of ± 0.14, which corresponds to ± 0.14 g's and approximately 30 percent of the lift margin from stall. Normally, a pilot will use no more than about 50 percent of the lift margin for control purposes with a 20-percent approach-speed margin above the stall. Thus, the direct lift control system had an authority of about 75 percent of that a pilot will normally use in landing approaches. The direct lift control system was considered to be a supplementary vernier control and not a replacement for conventional controls. The net pitching-moment change due to the flaps in the direct lift control authority range chosen is negligible in the Model A-3 and was assumed to be zero in the simulation.

Actuation of the flaps was achieved through a spring-centered, three-position toggle switch on the stick grip, that was referred to as the "lift switch." Except for the lag in control surface motion, the lift switch provided instantaneous direct lift control. The lift switch operated in the conventional longitudinal control and trim sense; pushing forward decreased the flap setting and lift, and pulling back increased the flap setting.

4.1.3 Tests

A series of tests was established to evaluate direct lift control over a wide range of basic longitudinal aerodynamic characteristics. These tests are summarized in Table III and include variations of phugoid and short-period frequency and damping, as well as operation on the backside of the thrust-required curve with conventional and exaggerated drag due to lift. The desired variations of the aerodynamic characteristics were obtained through adjustment of potentiometers 30 through 36, shown in Figures 4 and 5. The basic approach speed for the tests was 130 knots. This speed, as shown in Figure 7, corresponds to the minimum drag speed. An approach speed of 120 knots was used for tests 10, 11, and 12 to represent approaches on the backside of the drag curve. The induced drag of test 11 was arbitrarily increased by introducing a ΔC_{D_α} term. The resulting power-required curve with this term included is also shown in Figure 7. A total of 18 carrier-qualified pilot subjects were utilized during the test program. The assigned task was to make good carrier-landing approaches. No specific speed or glide-slope holding tasks other than keeping the speed within reasonable limits, avoiding the stall, and remaining as close to the ideal glide path as possible were given. Longitudinal trim, thrust, and altitude were automatically reset at the beginning of each approach for the proper trim speed and rate of descent. Each pilot subject flew each of the tests six times, three using direct lift control and three without direct lift control. Each test was initiated at a range of 6000 feet from the carrier at an altitude of 475 feet above the deck. Each flight was terminated at the ramp or about 300 feet from touchdown. In those tests in which the speeds were changed, tests 10 through 12, the carrier speed was adjusted to maintain the same relative speeds as in the first nine tests. Each test lasted approximately 30 seconds.

Random disturbances were introduced into the pitch, roll, and yaw channels by Gaussian noise networks with the high frequencies filtered out. The low-frequency disturbances were then adjusted to provide a maximum gust velocity of 10 feet per second based on studies of References 1 and 2. Calibration of the random noise network indicated the following angular-rate disturbances:

$$\Delta \dot{\gamma} = 1.9 \text{ degrees per second}$$

$$\Delta \dot{\phi} = 1.0 \text{ degrees per second}$$

$$\Delta \dot{\psi} = 0.6 \text{ degrees per second}$$

Vertical gusts with a duration of six seconds or greater were frequently encountered, and some pilots felt these to be unrealistic. In fact, although the gust magnitudes were based on apparently valid over-water gust surveys, some pilots also felt the disturbances to be unrealistically high. No attempt was made to simulate specific flow disturbances such as stackwash or downwash aft of the carrier.

4.1.4 Data

Data were obtained from the simulator in two forms:

1. REAC Brush Recording time histories of altitude error, rate of descent, angle of attack, elevator deflection, and flap deflection.
2. Magnetic tape recordings of altitude error and rate of descent from which IBM cards were punched for the data at one second intervals.

Pilot opinion data were also obtained in each test to determine whether the pilot felt that direct lift control increased, had no effect, or decreased his ability to make a good approach.

4.2 Results

The results of the subject investigation are presented in two forms:

(a) The percentages of the approaches waved off because of loss of meatball are presented in Table IV. Although no provisions were made for wave-offs in the simulator, those approaches in which the pilot actually two-blocked the meatball in the oscilloscope were eliminated from consideration. The simulated mirror landing system display had a meatball acquisition cone angle of 4.75 degrees. Actual MLS has a cone angle of ± 0.75 degrees. The simulated meatball acquisition cone angle was large by design to avoid damage to the equipment.

(b) Root-mean-square (rms) altitude error is presented as a function of time in Figures 8 through 12. Mean altitude error is not shown since it is of no consequence and would approach zero with no bias and a sufficient number of samples. A digital computer program was used to obtain these results from the magnetic tape and IBM card data. The altitude-error data are presented only for those approaches not waved off for loss of meatball. As a consequence, each test has a different sample size varying from 28 to 85 percent of the total approaches. The variation of the sample size is of no particular consequence. The relationship of the rms altitude error with direct lift control to that without direct lift control is preserved in all cases as the sample size is reduced to as low as 20 percent of the total runs by arbitrarily reducing meatball acquisition angle and discarding those runs that exceed the tightened tolerances. Although these data are presented as a function of time, they are not time histories. The rms altitude error from all the approaches of each test with and without direct lift control was evaluated at discrete time intervals and then presented as a function of time.

4.2.1 Wave-Off Percentages

The effects of aerodynamic characteristics variations and direct lift control on the percentage of wave-offs because of loss of the meatball are summarized in Table IV. Even with the enlarged meatball acquisition angle (± 4.75 degrees), as compared with that of actual mirror landing systems (± 0.75 degree), the percentage of wave-offs is considerably higher than that in actual carrier operation. The simulator was considerably more difficult to fly precisely than an actual airplane. The disparity is understandable since five degrees of freedom were being simulated, and the pilots had only basic flight instruments and the simulated mirror landing system for reference. The inability to fly simulated carrier landing approaches with the precision possible in actual operations is attributed primarily to the lack of full motion and visual cues. Full-scale gust-disturbance simulation may also have been excessively severe for fixed-base simulation and certainly contributed to the inability to maintain flight control precision. No significance is attached to wave-off percentage changes less than 5 percent.

Phugoid Period

As indicated by the data of Table IV, the percentage of wave-offs decreased from 42.6 percent to 31.5 percent as the phugoid period increased from 20 to 30 seconds, and then increased sharply to 55.6 percent as the period increased from 30 to 40 seconds. The indicated variation of wave-off percentage with phugoid period is very difficult to explain. Poorer control precision might be expected with a very slow and sluggish phugoid if altitude control were derived primarily from thrust control, but thrust was adjusted only as necessary to maintain speed as altitude errors were corrected by longitudinal control. As a consequence of the manner in which altitude errors were corrected, one would not expect to see any appreciable effect of phugoid period. The same trend is apparent with direct lift control, but to a lesser degree. Direct lift control had no particular effect on the wave-off percentages at the shorter phugoid periods but reduced the wave-offs considerably at the longer phugoid period.

Phugoid Damping

As indicated by the data of Table IV, phugoid damping variations had no particular effect on the wave-off variations without direct lift control. Except where the phugoid was very lightly damped, direct lift control had no effect on the wave-off percentages or the variation of wave-off percentage with phugoid damping. Direct lift control did, however, reduce the wave-off percentage from 35 percent to 15 percent where the phugoid damping was very light ($\zeta = 0.05$). A reduction in wave-offs would be expected where the phugoid is easily disturbed and not well damped, but the fact that the improvement is so marked, where there is little variation in wave-off percentages with phugoid damping variations without direct lift control, is surprising and somewhat of a mystery.

Short-Period Mode Period

Without direct lift control, the percentage of wave-offs increased from 31.5 percent to 37.0 percent as the period of the short-period mode increased from 6.5 seconds to 12 seconds and to 72 percent as the short-period mode became aperiodic (5-percent MAC unstable). This increase in the wave-offs as the airplane became less stable and unstable is quite reasonable. Direct lift control did not improve the wave-off percentage where the stability was good but did reduce the wave-offs considerably where the stability was low and where the airplane was statically unstable. The improvement due to direct lift control with low static stability and static instability would be expected, but the reduction in wave-off percentage with low static stability to less than that with higher static stability is surprising.

Short-Period Mode Damping

Reduction in damping of the short-period mode from 45-percent critically damped to 11-percent critically damped and to divergence resulted in an appreciable increase in wave-off percentages. It is somewhat surprising that the wave-off percentage was not increased more in the divergent situation, but otherwise the variation with short-period damping is reasonable. Direct lift control had no significant effect on the wave-off percentage with good short-period damping or where the short-period mode was divergent. It did reduce the wave-offs where the short-period was only lightly damped and, in effect, tended to smooth out the variation due to short-period damping variations.

Operation on Backside of Power-Required Curve

Reduction of the approach speed from 130 knots to 120 knots to represent operation on the backside of the power-required curve and arbitrarily increasing the induced-drag term to represent operation further on the backside of the power-required curve resulted in an expected increase in wave-off percentages. Providing additional excess thrust for the 120-knot case had no effect on the wave-off percentage. Direct lift control had no effect at the higher speed basic case but provided a marked improvement for those on the backside of the power-required curve. The improvement due to direct lift control at 120 knots was lost when additional excess thrust was provided. It would appear that in this case the pilots may have been too busy concentrating on use of throttle to use direct lift control effectively. Otherwise, the results of the tests of operation on the backside of the power-required curve are reasonable.

4.2.2 Altitude Error

The effects of aerodynamic characteristics variations and direct lift control on the root-mean-square altitude error are shown in Figures 8 through 12 in which rms altitude error during the last 24 seconds of the approaches is presented as a function of time. The altitude error permitted by the meatball acquisition cone angle (± 0.75 degree) of actual mirror landing system installations is also shown in Figures 8 through 12 for reference. It should be kept in mind that the simulated cone angle was ± 4.75 degrees and those approaches in which the simulated meatball was lost or two-blocked in the oscilloscope were not considered. The function of the meatball was maintained over the entire acquisition cone.

In actual operation, a very large initial altitude error would be expected. This error would decrease linearly with range to about 5 feet at the ramp. The simulated approaches were all initiated with zero altitude error 30 seconds from the ramp. Only the last 24 seconds are shown in Figures 8 through 12. The fact that the approaches were all initiated with no altitude error accounts for the relatively low error during the initial stages of the approaches where large errors would be expected.

The reduction in altitude error during the last 8 to 10 seconds of the approaches is indicative of increased meatball sensitivity at short ranges. This time range is considered to be the most significant in evaluation of the data. In some cases an improvement due to direct lift control, indicated in this time period, is dissipated at the ramp. This dissipation is not necessarily considered to be significant for two reasons:

1. Improved performance in the last 8 to 10 seconds reduces the necessity for undesirable last-second corrections.

2. There was a tendency among the pilots to focus on a goal of arriving at the ramp with a minimum altitude error. Altitude errors did not receive prompt attention until close to the carrier. The dangers of sloppy approaches with more or less radical maneuvering near the deck were being neglected in these cases.

Phugoid Period

The data of Figure 8 indicate the effects of phugoid period variation and direct lift control on rms altitude error. Direct lift control reduced the rms altitude error over the last 8 to 10 seconds from 5 to 10 feet at all three phugoid periods. This improvement was lost at the ramp for the two shorter periods where an rms altitude error of 10 to 12 feet is shown with and without direct lift control. The improvement was maintained to the ramp with the longer period, however.

Using the rms altitude error at t = 20 seconds as an index, the effects of phugoid period and direct lift control on altitude error are summarized as follows:

Test	Phugoid Period (seconds)	Altitude Error (feet) Basic	DLC
1	20	20.0	14.0
2	30	28.5	18.5
3	40	26.5	22.5

The basic altitude-error variation with phugoid-period variation is inconsistent with the wave-off-percentage variation, and neither variation is considered to be particularly characteristic to the phugoid-period variation. The altitude-error reduction due to direct lift control varies from 4 to 10 feet or 15 to 35 percent. Considering both the altitude-error and wave-off-percentage reductions, it is concluded that direct lift control provides a nominal improvement in flight path control precision at all reasonable phugoid periods.

Phugoid Damping

The effects of phugoid-damping variations and direct lift control on rms altitude error are shown in Figure 9 and are summarized for a characteristic time (t = 20 seconds) in the following table:

Test	Phugoid Damping	Altitude Error (feet) Basic	DLC
4	$\zeta = .04$	17.5	21.0
2	$\zeta = .08$	28.5	18.5
5	$\zeta = .12$	22.5	21.5

No particular significance is attached to the variation in basic altitude error with phugoid damping, and there seems to be no particular reason for the indicated variation. In fact, the altitude error with low phugoid damping appears to be unreasonably small. The altitude error with direct lift control with low phugoid damping is greater than without direct lift control, but as indicated in the previous section, direct lift control reduced the wave-offs in this particular test considerably. There is a considerable altitude-error reduction due to direct lift control with moderate phugoid damping but almost no improvement with higher phugoid damping. Considering both the altitude-error and wave-off percentage effects of direct lift control, it is concluded that the improvement in flight path control precision due to direct lift control increases as phugoid damping is reduced.

Short-Period Mode Period

The effects of static longitudinal stability or period variations of the short-period longitudinal mode and direct lift control on rms altitude error are shown in Figure 10 and are summarized briefly as follows:

Test	Period (seconds)	Altitude Error at t = 20 (feet) Basic	DLC
2	6.5	28.5	18.5
6	12.0	24.0	19.0
9	Aperiodic	39.0	28.0

Although less basic altitude error would be expected with a period of 6.5 seconds than with a period of 12 seconds, the variation of altitude error with static stability or period of the short-period mode is not unreasonable. Direct lift control reduced the altitude error from 5 to 10 feet over the range of periods tested. Note that although the altitude error is not reduced as much with a period of 12 seconds as with a period of 6.5 seconds or where the short-period mode is aperiodic, there is a large reduction in wave-offs with direct lift control in these cases. Considering both altitude-error and wave-off percentage it is concluded that direct lift control provides a nominal improvement in flight path control precision with normal static stability levels and a greater improvement as static stability is reduced.

Short-Period Mode Damping

The effects of short-period mode damping and direct lift control on altitude error are shown in Figure 11 and summarized briefly as follows:

Test	Damping	Altitude Error at t = 20 (feet) Basic	DLC
2	$\zeta = 0.45$	28.5	18.5
7	$\zeta = 0.11$	22.0	26.5
8	$\zeta = -.05$	27.0	18.0

The variation of basic altitude error with short-period damping variations does not correspond to expectations since an increase in altitude error with reduced damping and divergence would be expected. Direct lift control reduced the altitude error about 10 feet or 35 percent with good short-period damping and where the short-period mode was divergent. The altitude error was increased with direct lift control where the short-period mode was lightly damped. Direct lift control did, however, provide a significant reduction in wave-off percentage in this condition. It is concluded that in light of the altitude-error and wave-off percentage reduction, direct lift control provides a nominal improvement in flight path control precision that is not affected by short-period damping variations.

Operation on the Backside of the Power-Required Curve

The effects of operating on the backside of the power-required curves and direct lift control on altitude error are shown in Figure 12 and in the following table:

Test	Test Condition	Altitude Error at t = 20 (feet) Basic	DLC
2	V = 130 knots	28.5	18.5
10	V = 120 knots	20.0	18.0
11	V = 120 knots with increased induced drag	24.5	18.0
12	V = 120 knots with increased excess thrust	24.0	20.0

The basic altitude error variation as the approach is made further on the backside of the power-required curve appears to be unreasonable. An increase in altitude error corresponding to the increase in wave-off percentages would be expected. It may be that operating on the backside of the power-required curve increases the difficulty and pilot effort required to make good approaches without detracting significantly from the altitude control accuracy itself. Direct lift control reduced the altitude error in all cases. The reduction due to direct lift control is smallest in Test 10, but the reduction in wave-off percentage in this test condition was quite large. Considering both the wave-off-percentage and altitude-error reductions, it is concluded that direct lift control provides a considerable improvement in flight path control precision at speeds on the backside of the power-required curve. This improvement can reasonably be expected to permit reduction of the minimum landing approach speed where the approach speed is limited by such considerations.

4.2.3 Pilot Opinion

Pilots participating in the simulator tests were asked to rate direct lift control on the basis of whether in their opinion direct lift control increased, had no effect on, or decreased their ability to make a good landing approach. The results of these ratings are summarized in Table V, and as indicated by these data pilot opinion was strongly in favor of direct lift control. The percentage of pilots that were of the opinion that direct lift control improved their ability to make a good approach varied from test to test between 61 and 94 percent.

There appears to be no direct correlation between the pilot opinion of direct lift control as summarized in Table V and the wave-off percentages summarized in Table IV or the altitude-error data of Figures 8 through 12. One exception is the case of the statically unstable airplane in which 94 percent of the pilots preferred direct lift control. This configuration is clearly the most difficult to control precisely, and the pilots were almost unanimous in their preference for direct lift control. Review of individual pilot performance as indicated by the REAC Brush Recorder time histories also shows no correlation between performance and the pilot opinion variation. It appears that pilot opinion was based on four more or less obscure factors:

(a) Effort involved or ease with which slight altitude errors could be corrected by direct lift control.

(b) Ability to correct altitude errors without disturbing the airplane attitude or any unstable or poorly damped situation.

(c) Tendency of some pilots to base their judgement on final conditions rather than on over-all performance.

(d) The random nature of the simulated gust disturbances.

A two-hour practice period was required of each pilot prior to conducting the tests to insure familiarity with the simulator and the direct lift control system. All of the test subjects were experienced carrier pilots.

Airspeed data required to assess the ease or difficulty of maintaining speed and the effects of direct lift control on speed-holding ability were not recorded. Review of pilot opinion indicated no particular difficulty in maintaining speed except at speeds on the backside of the drag curve, and direct lift control apparently improved the ability to maintain speed in these cases.

4.2.4 Additional Comments

When the use of direct lift control for increased flight path control precision in carrier landing approaches was first conceived, it was thought some reduction in drag changes due to lift changes made for control purposes might be realized through direct lift control. This would increase the effectiveness of direct lift control. However, review of the aerodynamics indicates that drag changes due to lift changes through flap deflection are practically identical to normal drag due to lift changes at normal approach conditions. Thus, the effectiveness of direct lift control as a means of improving flight path control precision is primarily the result of other factors, such as reduction in response time and elimination of the necessity for disturbing the angle of attack or any characteristic mode that might not be sufficiently stable or well damped. However, at angles of attack corresponding to speeds well on the backside of the power-required curve, the drag change per unit lift change due to conventional flaps is less than the drag change per unit lift change due to angle of attack. Thus, in addition to the other factors involved, the aerodynamics of the situation are improved through direct lift control in approaches on the backside of the power-required curve.

In many of the test conditions, the improvement in altitude error due to direct lift control is only nominal. In a few other cases, direct lift control apparently increases the altitude error. Yet in all cases, pilots opinion indicated a preference for direct lift control. It would thus appear that the increase in ease in making the approach to any degree of accuracy is a most important factor. In fact, the reduction in pilot attention and effort required may very well be more important than improvement in control precision. It is also reasonable to expect that improvements in flight path control precision or handling qualities achieved through direct lift control can be translated into a reduction in minimum usable approach speed.

As a consequence of the conclusion that the primary reason for the effectiveness of direct lift control is not a reduction in drag changes due to lift changes, it would appear that use of direct lift control in conjunction with an automatic throttle compensation system would provide a most effective landing approach control system. Direct lift control alone should provide an improvement in landing approach control and should be evaluated on its own merits. However, ultimate combination of direct lift control and an automatic throttle compensation system should be considered.

Devotion of a nominal flap deflection to direct lift control does not necessarily reduce the margin from stall. The mistaken impression that it does has been expressed in many quarters. However, changing flap deflection has no significant effect on the stall angle of attack. On the other hand, increasing the angle of attack through nose-up longitudinal control does reduce the angle-of-attack margin from stall.

During the course of the subject tests, the thought arose that an integrating trim function could be incorporated in the direct lift control operating switch. If the pilot continually demanded lift changes in one direction or the other, the integrating trim function would slowly trim the angle of attack in that direction. If more or less equal increased-lift and decreased-lift commands were made, no change in trim would occur. Such a function seems to be quite desirable. It might be possible to incorporate the direct lift control function in the normal longitudinal trim switch. Unfortunately, many existing longitudinal trim systems have sufficiently serious reliability and maintenance problems so that the additional functions and complexity could not be afforded. The concept should be pursued further, however, if the opportunity arises.

Consideration of the use of direct lift control in landing approaches need not be restricted solely to carrier landing approaches. It could be used in any pilot controlled approach in which altitude-error information is available to the pilot, such as in ILS, GCA, and field MLS approaches. Direct lift control might also be adaptable to automatically controlled approaches.

5.0 CONCLUDING REMARKS

As has been found in numerous other tracking task investigations, there is not always a consistent variation of pilot tracking performance with the static and dynamic quality of "goodness" of the controlled element. This is generally attributable to the extreme adaptability of the human pilot. It is not surprising, therefore, that the quantitative data presented herein do not indicate conclusively the effects of aerodynamic configuration changes or of direct lift control. A liberal interpretation of the data, however, would permit the general observations that the aircraft with obviously poor flying qualities were most difficult to control precisely and that the benefits of direct lift control are most noteworthy for the poorest aircraft configurations.

Since the human pilot's adaptability frequently masks tracking performance as a criterion to judge the advantages or disadvantages of parameter variations, one must rely heavily on pilot opinion for guidance. In this investigation approximately 75 percent of the pilots were of the opinion that direct lift control improved their ability to make good landing approaches. This finding is considered to be significant.

On the basis of the results of this program, use of direct lift control as a means of improving flight path control precision during carrier landing approaches appears to be promising. Direct lift control appears to be most promising in those cases in which longitudinal handling qualities at desired approach speeds are deficient to the extent that approach precision is compromised and in those cases that minimum usable approach speed is limited by an adverse lift-drag relationship or excessive induced drag.

Installation of direct lift control systems in appropriate carrier-type airplanes and flight tests of the system are recommended. The following items should be tested in this program:

1. Direct lift control system authority.
2. Minimum usable approach speed effects.
3. Feasibility and effectiveness of an integrating trim function.
4. Direct lift control effectiveness in combination with an automatic throttle compensation system.
5. Operational procedures.

6.0 REFERENCES

1. McGregor, D. M.: Investigation of Low Level Turbulence Encountered by a Sabre MK-5 Aircraft Over Eastern Canada. National Aeronautical Establishment of Canada Report LR-298, January 16, 1961.

2. Roeser, Erwin P.: Low Altitude Gust Data Obtained in Fleet Aircraft. Naval Air Material Center Report No. NAMATCEN-ASL-1041, July 21, 1961.

TABLE I

SIMULATOR AND OSCILLOSCOPE

EQUATIONS

SIMULATOR EQUATIONS

$$\alpha = \alpha_o + \Delta\alpha_s + \Delta\alpha_T$$

$$\Delta\alpha_s = \frac{1}{s}\left[-\frac{T_d}{T_c}\Delta\alpha_s - \frac{1}{T_c}\frac{\Delta\alpha_s}{s} - \frac{1}{T_c}K_4\frac{\delta_e}{s} - \frac{T_b}{T_c}K_4\,\delta_e\right]$$

$$\Delta\alpha_T = \frac{C_{L_T}}{C_{L_\alpha}s}$$

$$\delta_e = -(\delta_s)_e$$

$$C_L = (C_L)_\alpha + \Delta C_{L_c}$$

$$\Delta C_{L_c} = \frac{\Delta C_{L_c}}{1 + T_a s}$$

$$C_D = (C_D)_{C_L} + \Delta C_{D_c}$$

$$\Delta C_{D_c} = \Delta C_{L_c} K_3$$

$$\dot{\gamma}_a = C_L K_2 V - \frac{g}{V} + \Delta\dot{\gamma}_R$$

$$\gamma_a = \frac{\dot{\gamma}_a}{s} + \gamma_o$$

$$\gamma_e = \gamma_a \cos\phi$$

$$\dot{V} = \frac{T}{m} - C_D K_2 V^2 - \gamma_a g$$

$$V = \frac{\dot{V}}{s} + V_o$$

$$A_z = g + \dot{\gamma}_a V$$

SIMULATOR EQUATIONS (continued)

$$h = \frac{V}{s}\,\gamma_e + h_o$$

$$R/C = V\gamma_e$$

$$\theta_a = \gamma_a + \Delta\alpha_s + \Delta\alpha_T$$

$$\theta_e = \theta_a \cos\phi$$

$$\phi = (\Delta\dot{\phi}_s + \Delta\dot{\phi}_R)\,\frac{1}{s} + \phi_o$$

$$\Delta\dot{\phi}_s = \frac{1}{s}\left[-\frac{1}{T_2}\,\Delta\dot{\phi}_s + \frac{1}{T_1T_2}\,\frac{\Delta\dot{\phi}_s}{s} + \frac{K_5}{T_1T_2}\,T_3\,\delta_a + \frac{K_5}{T_1T_2}\,\frac{\delta_a}{s}\right]$$

$$\delta_a = (\delta_s)_a$$

$$\dot{\psi}_e = \frac{A_z}{V}\,\phi$$

$$\psi_e = (\dot{\psi}_e + \Delta\dot{\psi}_R)\,\frac{1}{s} + \psi_o$$

$$X = X_o - \frac{V}{s} + \frac{V_c}{s}$$

$$R = X \cos\gamma_e$$

$$\Delta Z_a = h - R\,i_g$$

$$Y = Y_o + \frac{V}{s}\,\psi$$

$$T = m\left(\frac{K_1}{1 + T_f s}\right)\left(\frac{RPM}{RPM_{max}}\right)^3 \delta_T$$

TABLE I (con't)

OSCILLOSCOPE EQUATIONS

$$W_p = \frac{K_c}{R}$$

$$Y_L = K_a \left(\psi_e + \frac{Y}{R}\right)$$

$$Z_h = K_a \, \theta_e$$

$$Z_L = K_a \left(\theta_e + \frac{h}{R}\right)$$

$$Z_{MB} = \Delta Z_a \, \frac{K_b}{R^2}$$

TABLE II

MODEL A-3B

AERODYNAMIC CHARACTERISTICS

Center of Gravity	18.0% MAC
Gross Weight	45,922 Lb.
Rolling Moment of Inertia	165,720 Slug Feet Squared
Pitching Moment of Inertia	317,740 Slug Feet Squared
Yawing Moment of Inertia	453,010 Slug Feet Squared
Product of Inertia	9,120 Flug Feet Squared
Wing Span	72.5 Feet
Wing Area	779.0 Square Feet
Wing Mean Aerodynamic Chord	11.68 Feet
Approach Speed	130 Knots
Approach Angle of Attack	5 Degrees

C_{L_α} = 5.07 per radian

C_{D_α} = 0.40 per radian

C_{m_α} = -1.26 per radian

$C_{L_{D\alpha}}$ = 0.85 per radian

$C_{m_{D\alpha}}$ = -2.16 per radian

C_{L_q} = 4.5 per radian

C_{m_q} = -11.52 per radian

$C_{L_{\delta_e}}$ = 0.259 per radian

$C_{m_{\delta_e}}$ = 0.660 per radian

C_{l_β} = -0.196 per radian

C_{n_β} = 0.1315 per radian

C_{Y_β} = -1.06 per radian

$C_{l_{\delta_a}}$ = 0.244 per radian

$C_{n_{\delta_a}}$ = -0.002 per radian

C_{l_p} = -0.406 per radian

C_{n_p} = -0.112 per radian

C_{Y_p} = 0.518 per radian

TABLE III

TEST CHARACTERISTICS

Test No.	Characteristic Investigated	Variable	Indicated Airspeed V_o (Knots)	Dynamic Longitudinal Characteristics P_L (Seconds)	ζ_L	P_S (Seconds)	ζ_S
1.	Phugoid	P_L = 20 sec.	130	20	.08	6.5	.45
2.	Phugoid[1]	P_L = 30 sec.	130	30	.08	6.5	.45
3.	Phugoid	P_L = 40 sec.	130	40	.08	6.5	.45
4.	Phugoid	$\zeta_L = .04$	130	30	.04	6.5	.45
5.	Phugoid	$\zeta_L = .12$	130	30	.12	6.5	.45
6.	Short Period	P_S = 12 sec.	130	30	.08	12.00	.41
7.	Short Period	$\zeta_S = .11$	130	30	.08	6.5	.11
8.	Short Period	$\zeta_S = -.05$	130	30	.08	6.5	-.05
9.	Short Period	$C_{M_{C_L}} = + .05$	130	30	.08	-	-
10.	Phugoid [1][2]	ΔC_{D_α}[3] = 0	120	28	.10	8.0	.48
11.	Phugoid[2]	ΔC_{D_α}[3] = 1.0	120	-	-	8.0	.48
12.	Phugoid[2]	ΔT[4] ΔC_{D_α}[3] = 0	120	28	.10	8.0	.48

(1) Basic Case
(2) Operation on Backside of Thrust-Required Curve
(3) Potentiometer Number 34 (See Figure 4)
(4) Excess Thrust Available to Pilot Through Throttle

TABLE IV

Effect of Direct Lift Control on Wave-off Percentages

Test	Variable	Wave-off Percentage Basic	Wave-off Percentage With Direct Lift Control
	Phugoid Period		
1	P = 20 seconds	42.6	46.3
2	P = 30 seconds	31.5	35.2
3	P = 40 seconds	55.6	40.7
	Phugoid Damping		
4	ζ = .04	35.2	14.8
2	ζ = .08	31.5	35.2
5	ζ = .12	38.9	40.7
	Short-Period Mode Period		
2	P = 6.5	31.5	35.2
6	P = 12	37.0	22.2
9	P = ∞	72.2	53.7
	Short-Period Mode Damping		
2	ζ = .45	31.5	35.2
7	ζ = .11	40.7	33.3
8	ζ = -.05	42.6	38.9
	Backside of Power-Req'd Curve		
2	130 kts	31.5	35.2
10	120 kts	44.4	29.6
11	120 kts (increased induced drag)	63	48.1
12	120 kts (increased excess thrust)	46.3	42.6

TABLE V

PILOT OPINION SUMMARY

Test	Category A	Category B	Category C	Percentage of Pilots in Category A
1	11	6	1	61
2	12	2	4	67
3	11	5	2	61
4	14	3	1	78
5	13	4	1	72
6	14	4	0	78
7	13	4	1	72
8	15	1	2	83
9	17	0	1	94
10	14	3	1	78
11	11	5	2	61
12	13	4	1	72

A - Number of pilots who felt that direct lift control increased their ability to make good carrier landing approaches.

B - Number of pilots who felt that direct lift control had no effect on their ability to make good carrier landing approaches.

C - Number of pilots who felt that direct lift control decreased their ability to make good carrier landing approaches.

FIGURE 1

FIGURE 2

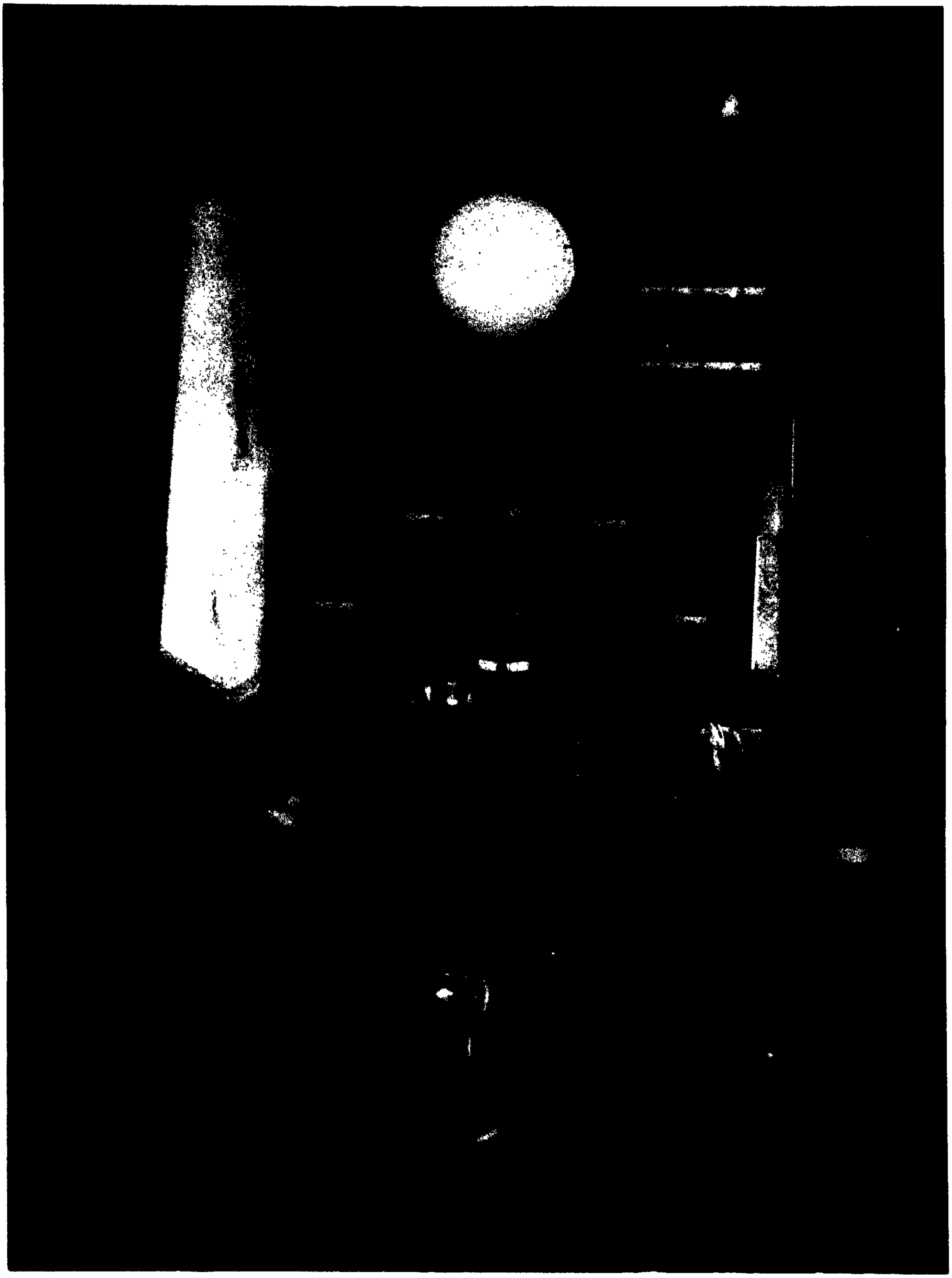
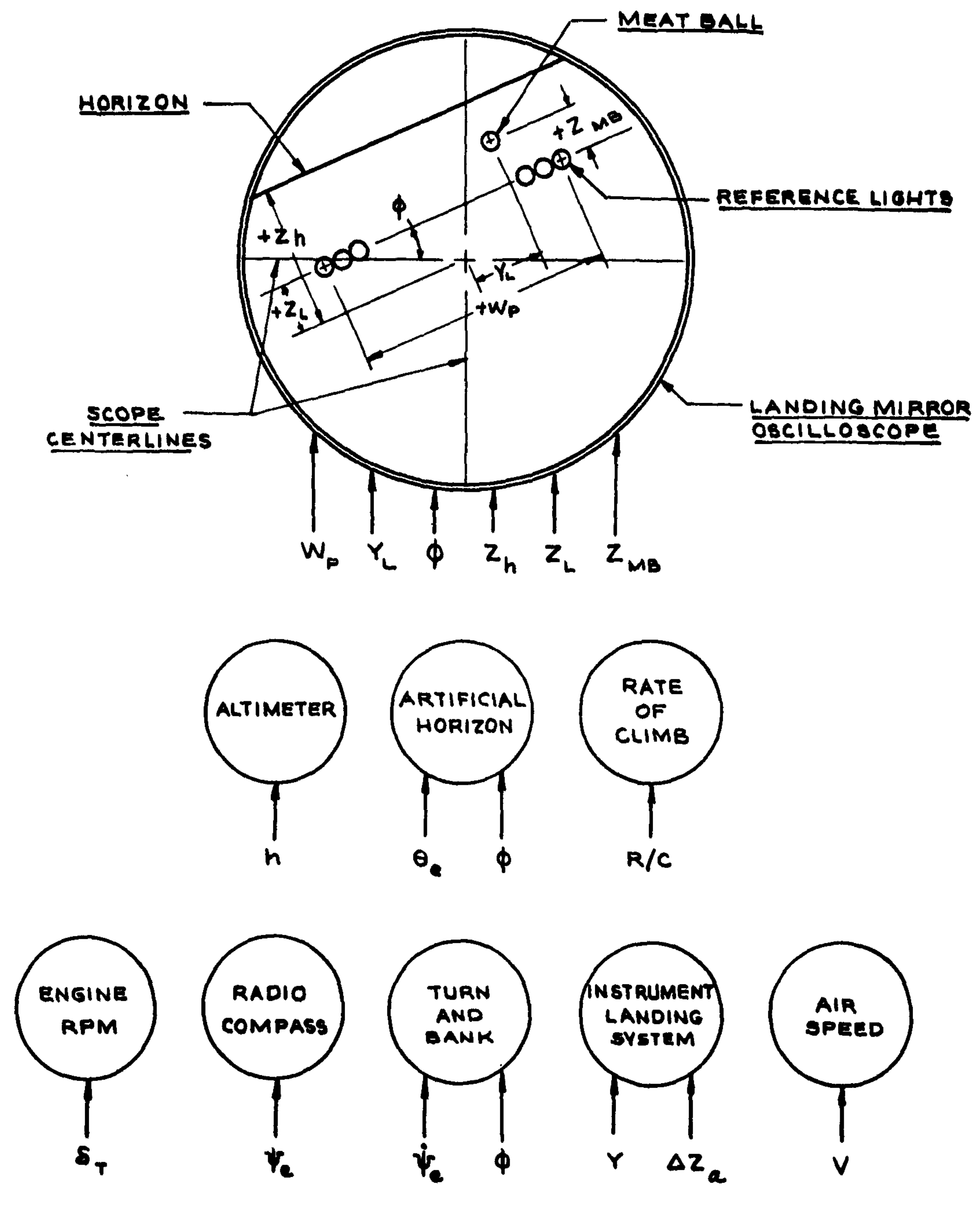


FIGURE 3

LANDING MIRROR OSCILLOSCOPE AND FLIGHT INSTRUMENTS

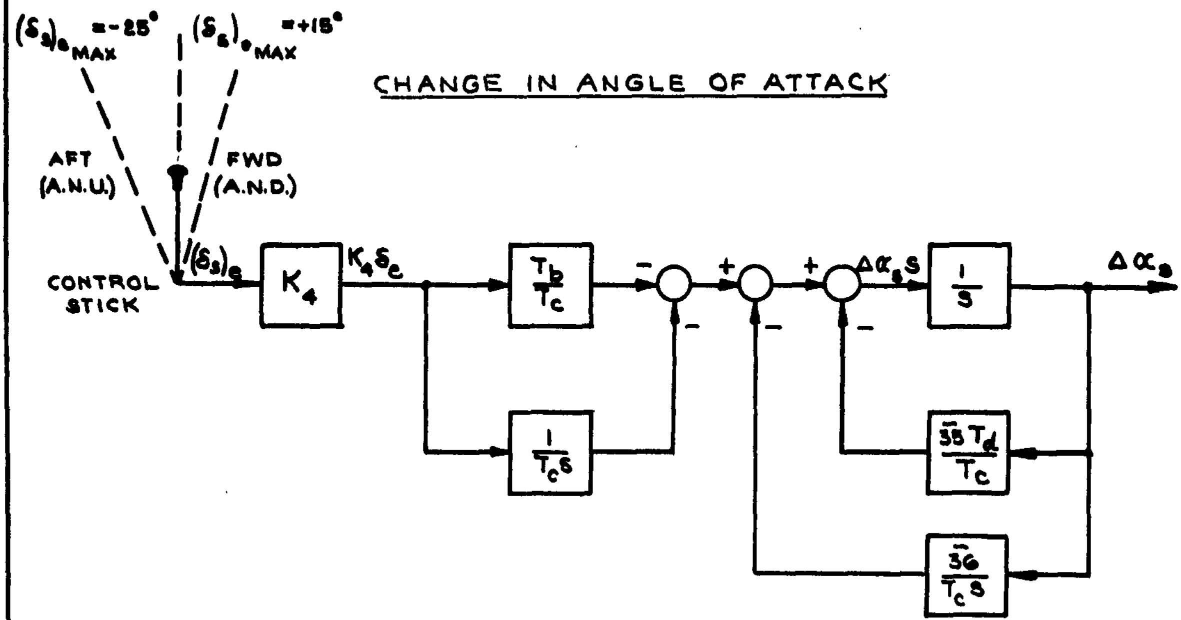


DOUGLAS AIRCRAFT COMPANY, INC. EL SEGUNDO DIVISION EL SEGUNDO, CALIFORNIA

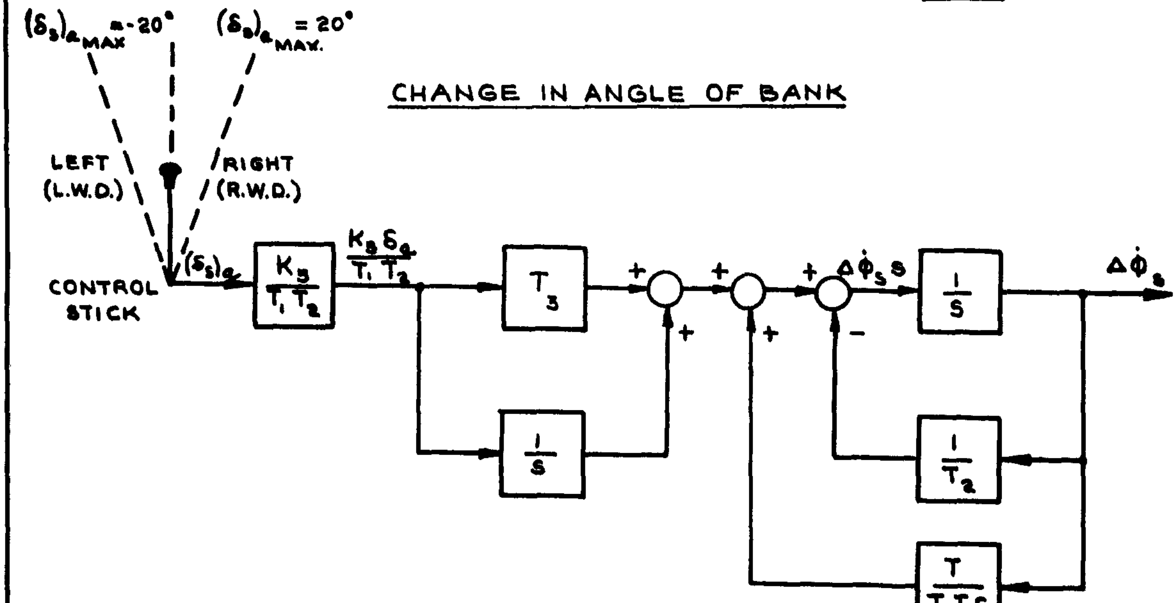
FIGURE 4

BLOCK DIAGRAMS FOR CHANGE IN ANGLE OF ATTACK AND ANGLE OF BANK WITH CONTROL STICK DEFLECTION

CHANGE IN ANGLE OF ATTACK



CHANGE IN ANGLE OF BANK



FORM 30-258 (7-51)

BLOCK DIAGRAM FOR CARRIER L

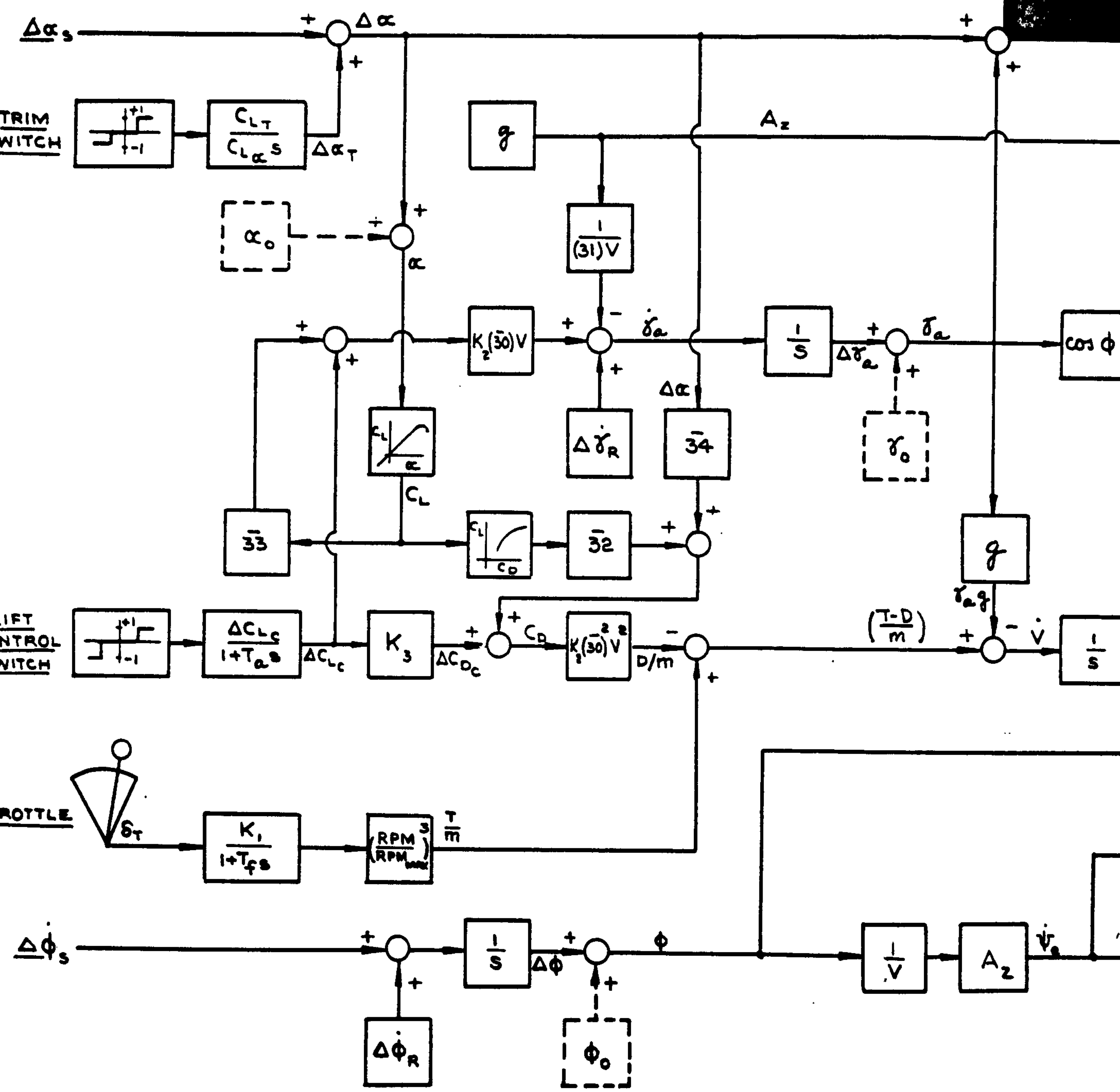


FIGURE 5

2

RRIER LANDING SIMULATOR

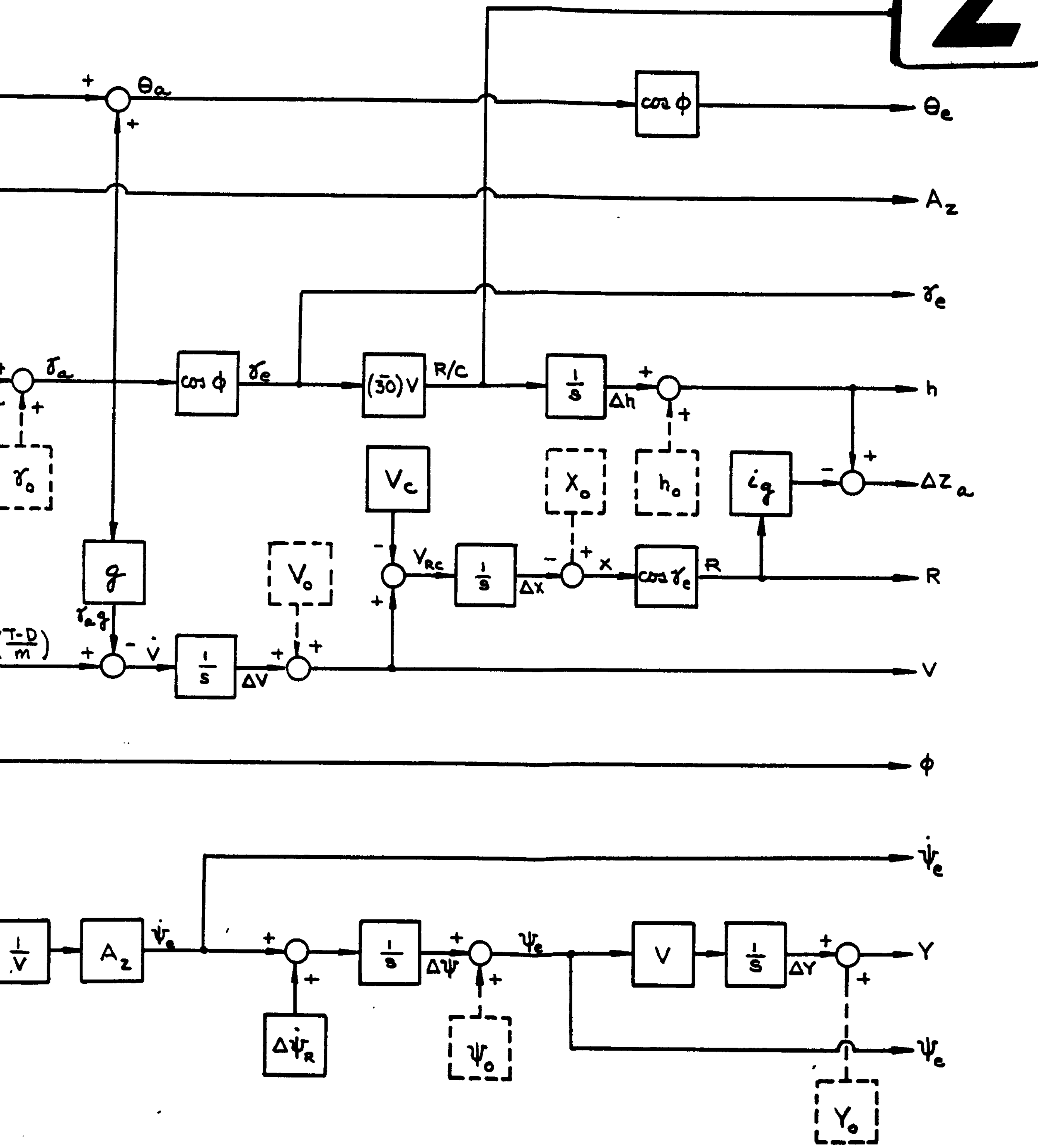


FIGURE 6

BLOCK DIAGRAM OSCILLOSCOPE EQUATIONS

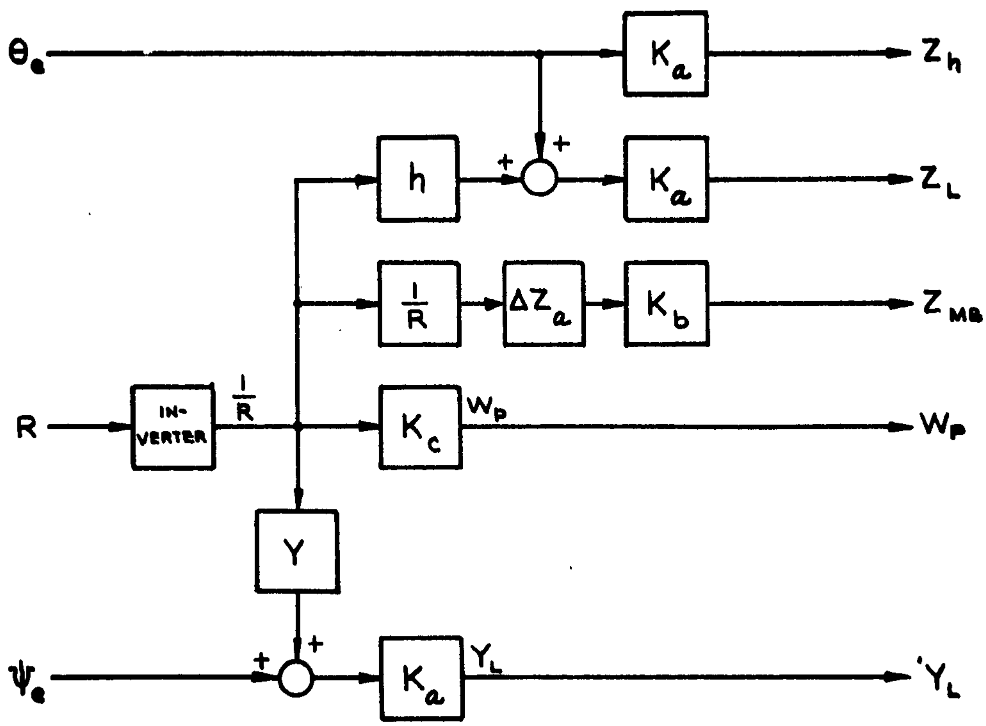


FIGURE 7

MODEL A-3B

VARIATION OF THRUST REQUIRED FOR LEVEL FLIGHT WITH SPEED

POWER APPROACH CONFIGURATION

WEIGHT = 46,000 LB.

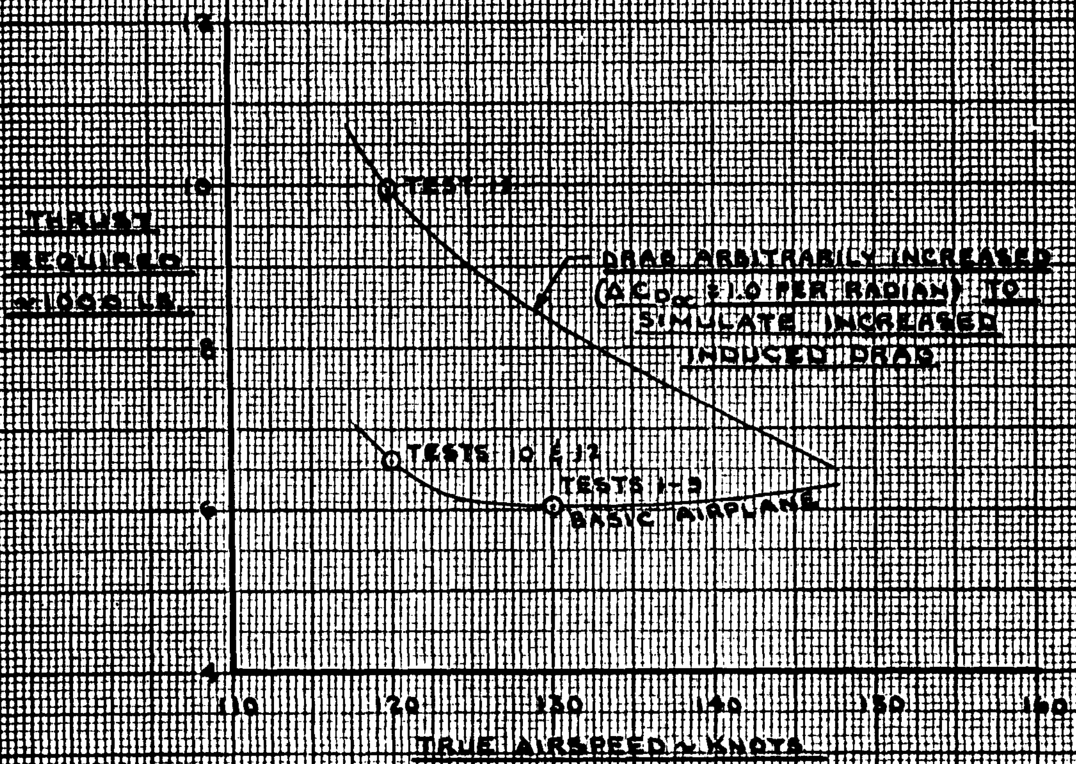


FIGURE 8

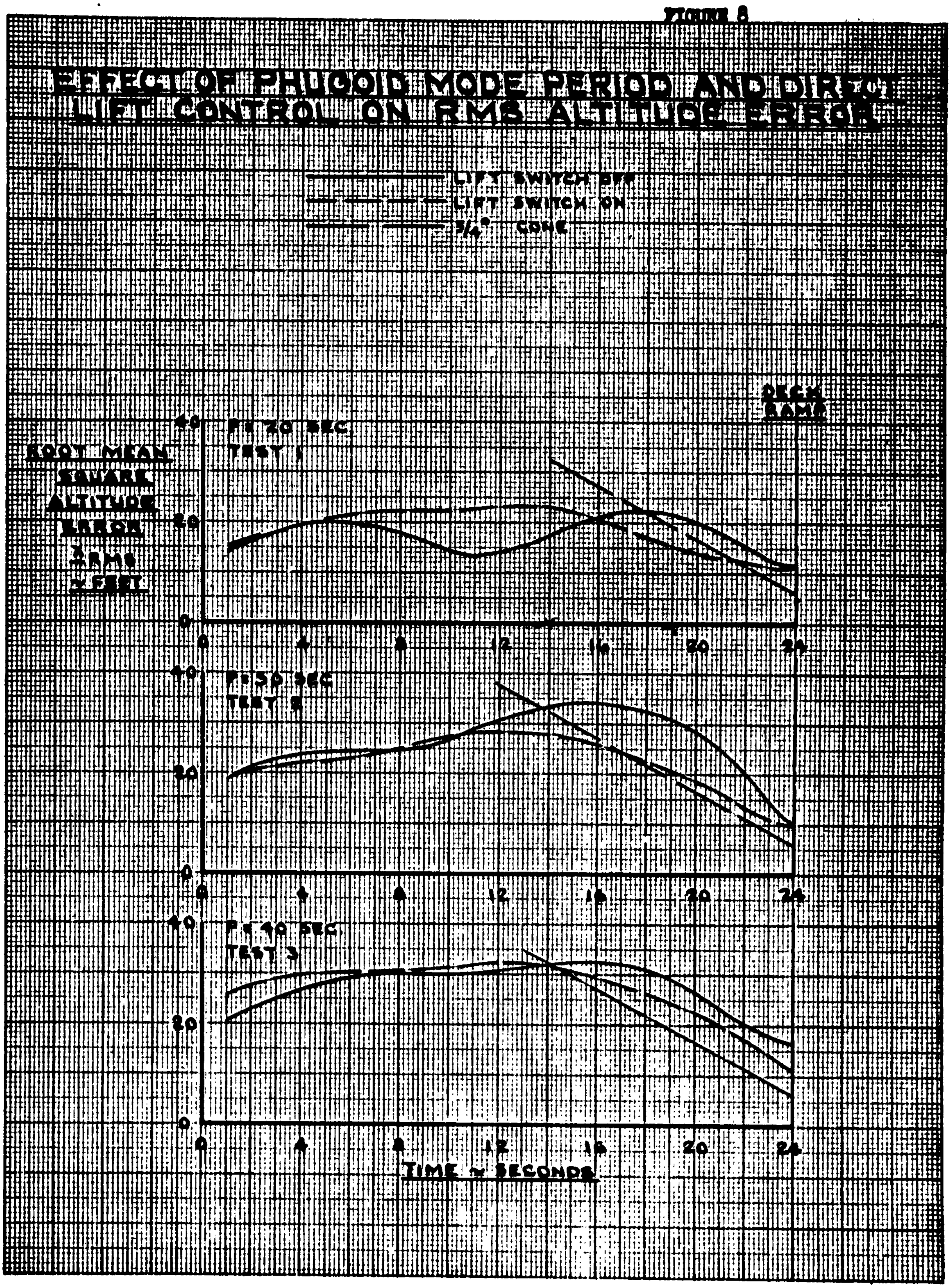

EFFECT OF PHUGOID MODE PERIOD AND DIRECT LIFT CONTROL ON RMS ALTITUDE ERROR
LIFT SWITCH OFF
LIFT SWITCH ON
3/4° CONE
DECK RAMP
ROOT MEAN SQUARE ALTITUDE ERROR
~ RMS ~ FEET
P = 20 SEC TEST 1
P = 30 SEC TEST 2
P = 40 SEC TEST 3
40
20
0
4
8
12
16
20
24
TIME ~ SECONDS

FIGURE 9

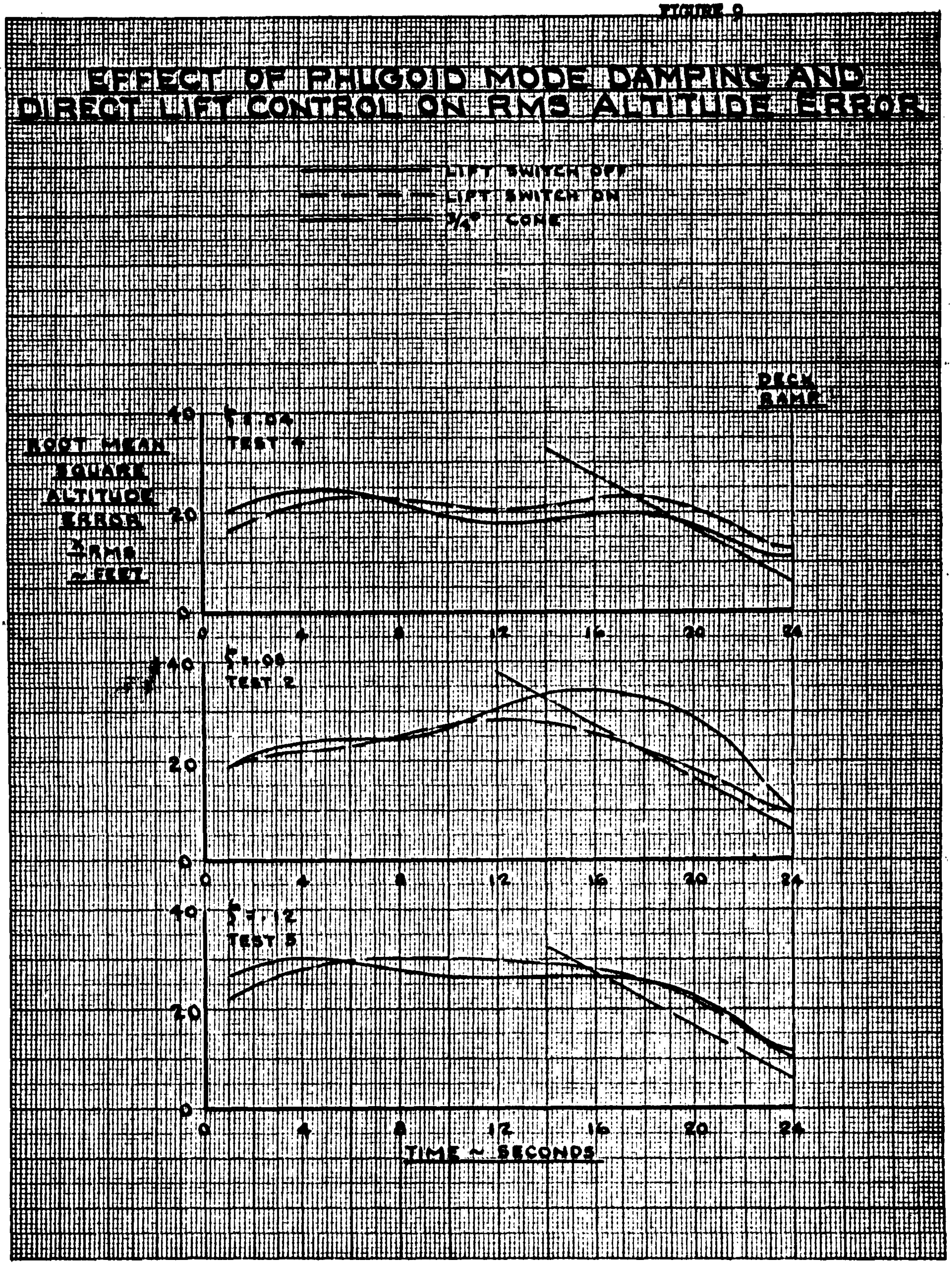

EFFECT OF PHUGOID MODE DAMPING AND
DIRECT LIFT CONTROL ON RMS ALTITUDE ERROR
LIFT SWITCH OFF
LIFT SWITCH ON
3/4° CONE
DECK RAMP
ROOT MEAN SQUARE ALTITUDE ERROR
Δ RMS ~ FEET
ζ = .04
TEST 4
ζ = .08
TEST 2
ζ = .12
TEST 5
40
20
0
0
4
8
12
16
20
24
TIME ~ SECONDS

FIGURE 10

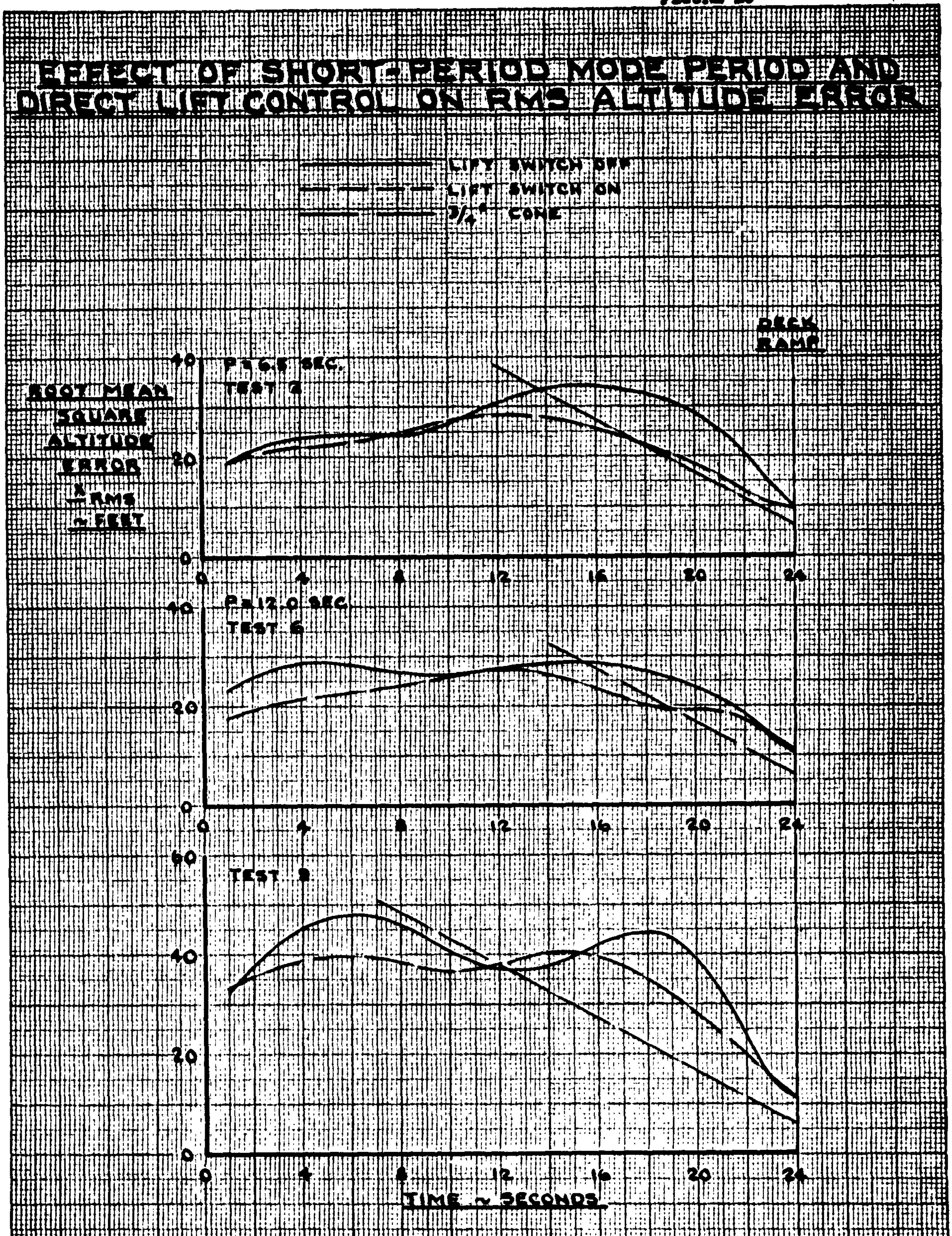

EFFECT OF SHORT PERIOD MODE PERIOD AND DIRECT LIFT CONTROL ON RMS ALTITUDE ERROR
LIFT SWITCH OFF
LIFT SWITCH ON
3/4° CONE
DECK
RAMP
ROOT MEAN SQUARE ALTITUDE ERROR
X RMS ~ FEET
P = 6.5 SEC.
TEST 2
P = 12.0 SEC.
TEST 6
TEST 9
TIME ~ SECONDS

FIGURE 11

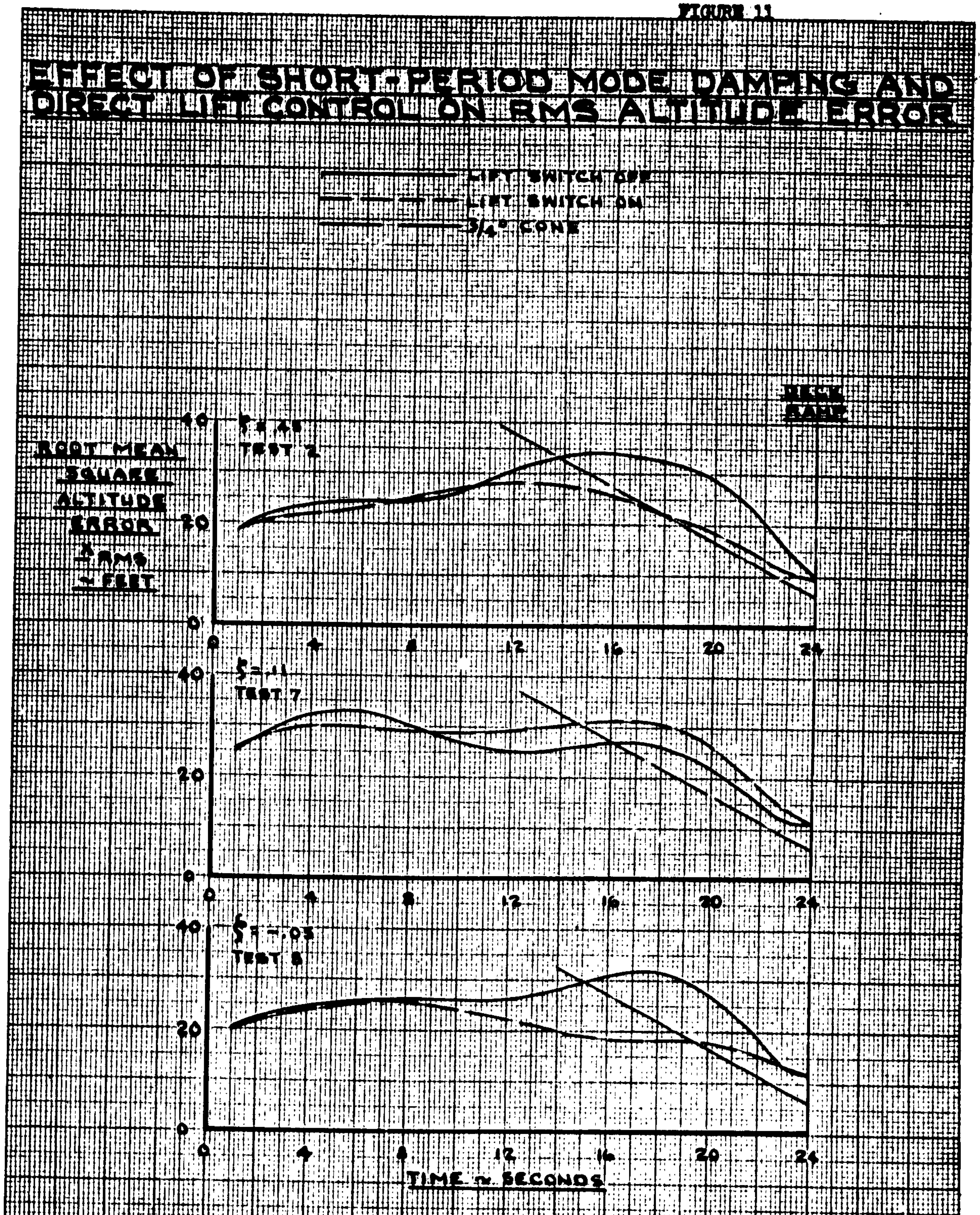
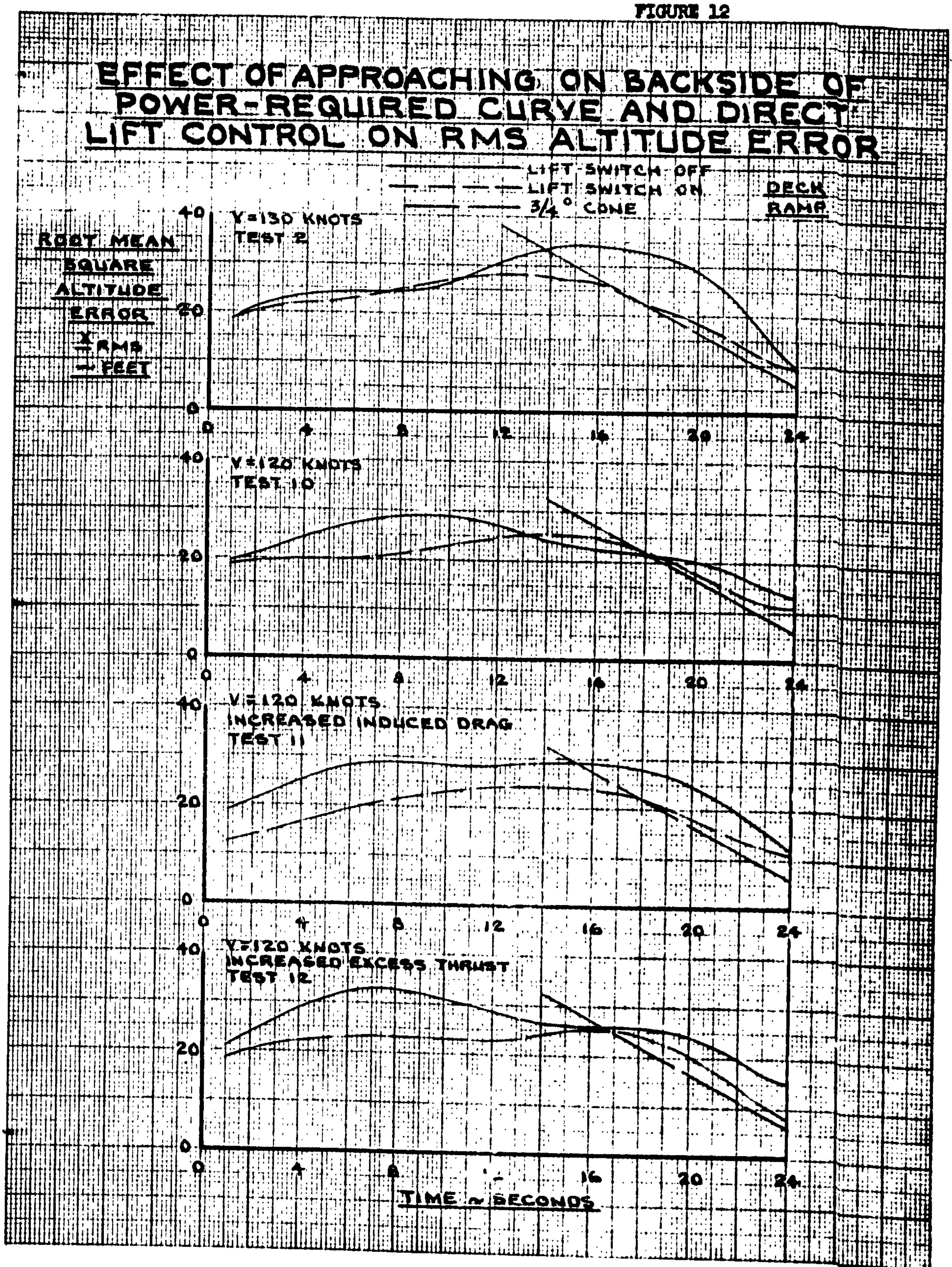

EFFECT OF SHORT-PERIOD MODE DAMPING AND DIRECT LIFT CONTROL ON RMS ALTITUDE ERROR
LIFT SWITCH OFF
LIFT SWITCH ON
3/4° CONE
DECK RAMP
ROOT MEAN SQUARE ALTITUDE ERROR
h RMS ~ FEET
TEST 2
ζ = .11
TEST 7
ζ = -.05
TEST 8
0
20
40
4
8
12
16
20
24
TIME ~ SECONDS

FIGURE 12


EFFECT OF APPROACHING ON BACKSIDE OF POWER-REQUIRED CURVE AND DIRECT LIFT CONTROL ON RMS ALTITUDE ERROR
LIFT SWITCH OFF
LIFT SWITCH ON
3/4° CONE
DECK RAMP
ROOT MEAN SQUARE ALTITUDE ERROR
X RMS ~ FEET
V=130 KNOTS
TEST 2
V=120 KNOTS
TEST 10
V=120 KNOTS
INCREASED INDUCED DRAG
TEST 11
V=120 KNOTS
INCREASED EXCESS THRUST
TEST 12
TIME ~ SECONDS